

ACOUSTIC RADIATION FROM
COMPRESSIVELY LOADED ICE

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ABSTRACT

The sound intensity of acoustic emissions from compressively loaded ice specimens was investigated. Distinct real-time intensities were measured in the near field of the specimens. The emissions exhibited unique frequency signatures with preferred directionality normal to the orientation of the applied load. When the strain rate was decreased, the emissions were attenuated.

INTRODUCTION

In the Arctic, ice has been used to construct islands which serve as offshore platforms. As a shifting, flowing mass, however, ice is a hazard which is able to destroy both frozen and conventional offshore structures (1). When ice is utilized as a building foundation, crack formation is detrimental, while when ice is impacting on an engineering structure, crack formation leads to disintegration of the ice and is therefore desirable. Both the estimation of ice strength for foundation purposes and the prediction of ice loading for offshore structure design require an ability to predict the formation and propagation of cracks in ice under mechanical loading (1).

From fracture mechanics, we know that crack formation occurs in a material (such as ice) under load when the surface energy of the newly formed crack surfaces is balanced by the release of potential energy stored through the elastic deformation of the material (2). This release of energy occurs as an elastic wave which propagates through the material, and is transformed into an acoustic wave at the surface. Recent research has been directed towards developing a relationship between the acoustic emissions from ice and (i) levels of stress and strain and (ii) crack formation and propagation (1,3,4,5,6).

Previous acoustic emission studies (3,4,5,6) have been limited to reporting the number and/or rate of emissions without regard to the directionality of the emissions in their true frequency spectra. Conventional acoustic emission techniques use a tuned bell mounted on the surface of a material. The energy of the acoustic pulse is deduced from parameters such as the ring-down count from the bell (2). This method yields a scalar measure of the emission amplitude at frequencies which are a function of the bell properties.

A sound intensity energy-flow mapping application called Dynamic Acoustic Intensity Scanning (DAIS) has been developed at the Centre for Cold Ocean Resources Engineering (C-CORE) (7,8,9,10,11). The DAIS technique measures the energy flow in materials as radiated by ambient vibration. The method involves automated data collection, measurement of sound intensity with real time digital filters, and vectorial analysis.

The DAIS approach was used to directly measure, in situ, the sound intensity of the emissions from ice undergoing cracking due to compressive loading. This paper characterizes the emissions as a set of intensities, and since sound intensity is a vector quantity, the intensity of the emissions traces the flow of acoustic energy from sources within the ice. In addition, the emissions are collected over a spectrum of frequency bands in real time, thus permitting an examination and identification of the frequency signature of each emission. Neither of these practices are possible using current acoustic emission techniques. The intensity approach described in this paper is termed "acoustic radiation" by the authors.

Background: Sound Intensity

Historically, acoustical measurements in air have been restricted to capturing sound pressure. Sound pressure is a scalar quantity, and hence, has no directional information. Sound intensity is, however, a vector quantity which indicates both the magnitude and direction of energy flow. A simple definition for sound intensity is a vector quantity that describes the net amount and direction of the flow of acoustic power at a given point in space (where intensity is in W/m^2 and intensity level is in $\text{dB re } 1 \text{ pW/m}^2$). In a medium without flow (i.e. without bulk movement of the medium) the intensity vector, I , is equal to the time-averaged product of the instantaneous

pressure, $p(t)$ and the corresponding particle velocity, $V(t)$, at the same point (12):

$$I = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{+\frac{T}{2}} p(t) \cdot V(t) dt$$

The intensity vector component in a given direction is:

$$I_r = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{+\frac{T}{2}} p(t) \cdot V_r(t) dt$$

Sound fields have both active and reactive components. Ambient noise is predominantly reactive and tends to have low particle velocities. Radiated vibrational energy (such as from an ice specimen undergoing cracking) forms active fields with high particle velocities. Since intensity utilizes the instantaneous particle velocity in its calculation it is possible to acquire intensity data which have high signal (active component) to noise (reactive component) ratios, even in noisy environments.

METHODOLOGY

Two cylindrical ice specimens (54 mm diameter by 135 mm long) were loaded in compression using a servo-hydraulic load frame. A dummy steel specimen was also loaded to determine the effects of the load frame. Two intensity analyzers were set up to measure the acoustic signals emitted from each specimen. Two pairs of closely spaced microphones and a finite pressure difference approximation for the particle velocity at a point midway between the microphone pairs were employed to capture the radiated intensities. This apparatus is illustrated in Figure 1. The two microphone pairs were set up to measure the sound intensities parallel to the applied load (X-direction) and normal to the applied load (Y-direction).

The two analyzers were programmed to collect simultaneous frequency spectra. Each intensity analyzer produces intensity levels in a spectrum of third-octave frequency bands with centre frequencies of up to 10 KHz, the upper limit of the analyzer.

For the first specimen, one hundred frequency spectra of acoustic radiation were collected over a 250 second period which encompassed the load cases illustrated in Figure 2(a). For each spectrum sample, linear averaging was conducted over a 250 millisecond period while the total time for processing each spectrum was 2.5 seconds. The specimen was strained at a rate of 0.08 mm/s for 50 seconds, resulting in microcrack formation and propagation. At this point the test frame was stopped for 135 seconds, after which the damaged specimen was strained a further 4 millimetres over a 5 second period (0.8 mm/s). Data collection continued for 60 seconds after the 5 second load cycle.

A second specimen of ice was tested in conjunction with a dummy steel cylinder of the same dimensions. The steel specimen was used to evaluate the background acoustic noise due to the loading apparatus and the experimental environment. The two analyzers were again programmed to collect simultaneous frequency spectra. Exponential averaging was set to 500 milliseconds and the total time for processing each spectrum was 0.75 seconds. Six hundred frequency spectra were collected for loadings at a strain rate of 0.013 mm/s for 400 seconds. The load cycle is illustrated in Figure 2(b).

RESULTS AND INTERPRETATION

Ice Specimen 1

Two load cycles were applied to the first specimen (see Figure 2(a)). The resulting emissions differ in response to the condition of the ice in each

cycle. The 50 second load cycle was applied to virgin ice, while the 5 second cycle was applied to ice which was damaged during the 50 second cycle.

Acoustic radiation which is evident between the load cycles in Figures 3(c) and 3(d) is thought to be a result of emissions associated with the relaxation of the ice crystals.

Fifty Second Load Cycle:

The first emissions from the ice during the 50 second load cycle are noted in the 2.5 KHz third-octave frequency band (see Figure 3(b)). The peak of the acoustic radiation occurs during the initial portion of the cycle and is oriented normal to the applied load (the Y direction in Figure 1), indicating the preferred directionality of the emission. The location of this peak corresponds to the the peak load applied during the 50 second cycle (Figure 2(a)). This implies that the maximum load is related to the highest amplitude acoustic radiation. The amplitude of the peak radiation measured during the 50 second load cycle increases with each consecutively higher frequency band, reaching a maximum for the 10.0 KHz band. This amplification of the radiation with increasing frequency is illustrated by comparing Figures 3(b) (2.5 KHz), 3(c) (6.3 KHz), and 3(d) (10.0 KHz).

Five Second Load Cycle:

The 0.315 KHz third-octave frequency band of the acoustic radiation exhibits ambient noise over the entire data collection period, except during the 5 second load cycle (see Figure 3(a)). For the 5 second load cycle, a peak amplitude is clearly evident for the Y component. This peak is present during the 5 second load cycle for all third-octave frequency bands examined (0.315 to 10.0 KHz) and is dominant in the low frequency bands. The directionality of the radiation is delineated by the large amplitude of the Y component compared to that of the X component. The origin of this peak is associated

with (i) the higher strain rate of the 5 second load cycle and (ii) the previous damage of the ice during the 50 second load cycle. Before and after the 5 second load cycle in Figure 3(a), the similarity between the amplitudes of the acoustic radiation in both the X and Y directions indicates the omnidirectional character of the reactive noise field. For third-octave frequency bands with centre frequencies greater than 2.5 KHz, the amplitude of the radiation measured during the 5 second cycle diminishes with increasing frequency. This is evident when the plots of Figures 3(b) (2.5 KHz), 3(c) (6.3 KHz), and 3(d) (10.0 KHz) are compared. The attenuation of the radiation at the high end of the frequency spectrum indicates that the emissions from the previously damaged ice are primarily "low" frequency (2.5 KHz or less).

Ice Specimen 2

Figures 4 to 6 display the results from the testing of ice specimen 2. Each intensity versus time graph corresponds to the load versus time graph of Figure 2(b).

The three plots of Figure 4 exhibit the Y component of the acoustic radiation for third-octave frequency bands centered at 10.0, 8.0, and 6.3 KHz. There is a prominent peak of intensity at the 36 second mark for each frequency band. The peak load occurred at the 60 second mark (see Figure 2(b)). In Figure 5 the X component is plotted for the 10.0, 8.0 and 6.3 KHz frequency bands. The amplitude of the signals in the X direction are relatively lower than those of the Y direction in Figure 4. In particular, the peaks seen in Figure 4 are virtually absent in Figure 5. This is concordant with the results for specimen 1, indicating a strong preferred radiation in the direction normal to the applied load.

In the 6.3 KHz frequency band the amplitude of the peak for specimen 2 (see Figure 4(a)) at a strain rate of 0.013 mm/s is 10.0 dB lower than that for specimen 1 at a strain rate of 0.08 mm/s during the 50 second load cycle (see Figure 3(c)). A similar 10.0 dB difference is seen between the peak amplitudes in Figures 4(c) (specimen 2) and 3(d) (specimen 1) for the 10.0 KHz frequency band. The trend is thus towards an attenuation of the acoustic radiation with decreasing strain rate.

Dummy Steel Specimen

To determine the effects of the load frame a dummy steel specimen was subjected to the the load cycle of Figure 2(b) and the emissions were recorded. Typical levels in both the X and Y directions are shown in Figure 6 for the 8.0 KHz frequency band. During the loading there are no peaks for the dummy specimen (see Figures 6(a) and 6(b)). Peaks noted during the compression of the ice for the Y component (see Figure 6(c)) are therefore descriptive of the ice behavior. For the X component (see Figure 6(d)), there is little difference between the emissions from the ice (see Figure 6(d)) and those from the dummy steel specimen (see Figure 6(b)). The dominance of the Y component again illustrates the preferred directionality and character of the acoustic radiations and demonstrates the advantage of using sound intensity over ringdown count bell measurements.

CONCLUSIONS

Acoustic radiation from the virgin ice occurred at third-octave frequency bands centered from 2.5 KHz up to 10.0 KHz (the upper frequency limit of the intensity analyzers). In each frequency band the peak amplitude radiation occurred close to the peak loading of the ice. The radiation was strongest at the highest frequency bands (8.0 and 10.0 KHz). Lowering the strain rate resulted in the attenuation of the acoustic radiation. The

radiation exhibited a preferred directionality normal to the orientation of the applied load (the Y-direction in Figure 1).

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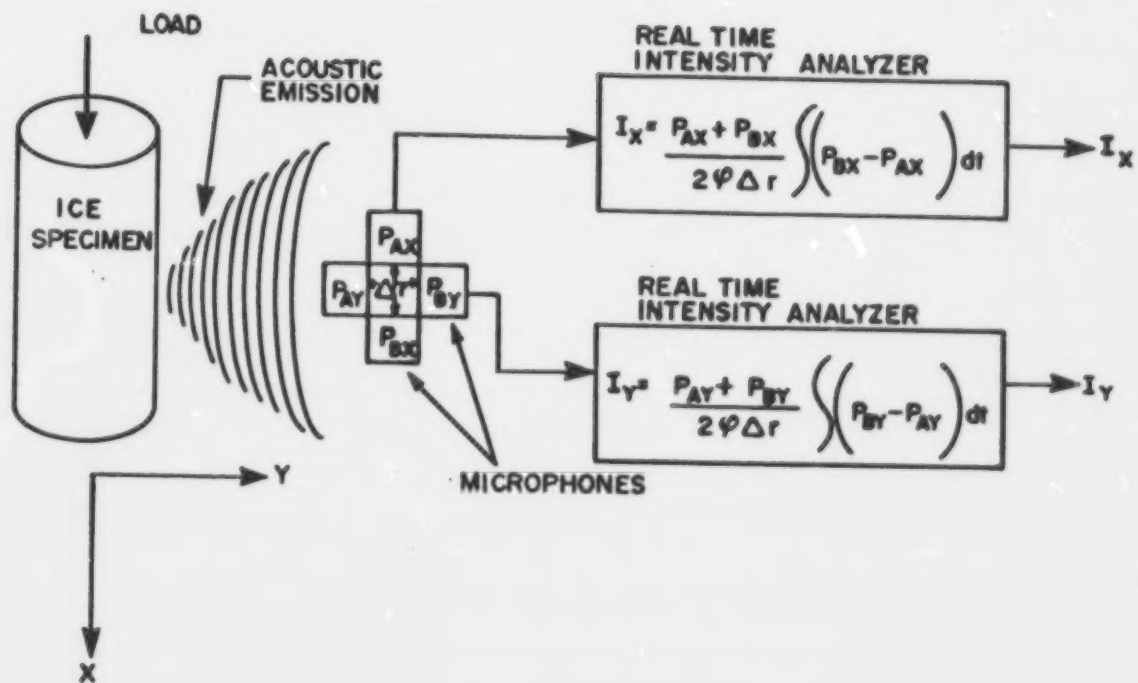
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FIGURE CAPTIONS

- Figure 1: Schematic layout of experimental setup.
- Figure 2: Compressive load cycles applied to (a) ice specimen 1 and (b) ice specimen 2.
- Figure 3: Plots of sound intensity amplitude versus time for ice specimen 1.
- Figure 4: Plots of Y-component of sound intensity amplitude versus time for ice specimen 2.
- Figure 5: Plots of X-component of sound intensity amplitude versus time for ice specimen 2.
- Figure 6: Plots of sound intensity versus time for ice specimen 2 and dummy steel specimen.

FIG. 1



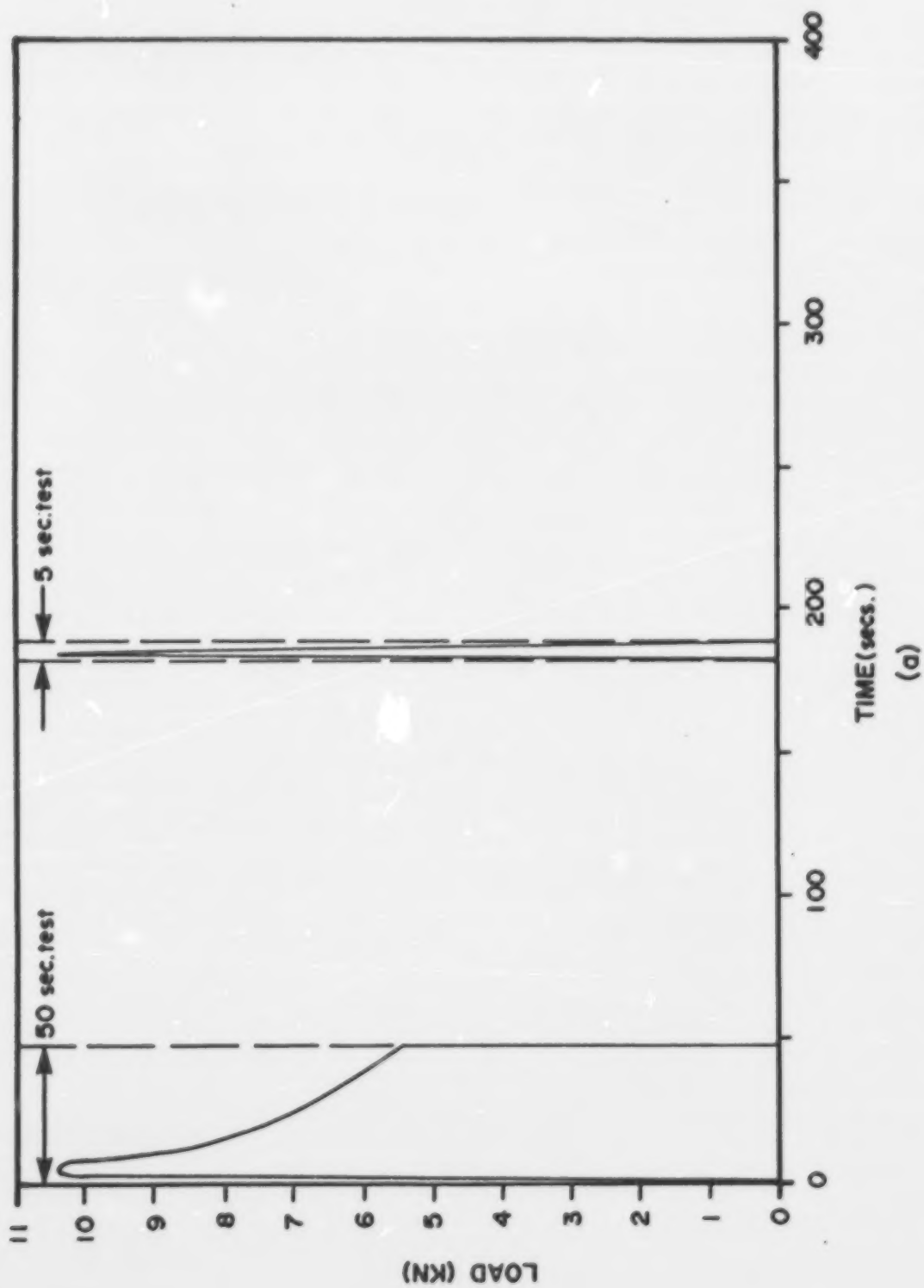


Fig. 2(a)

Fig. 2(b)

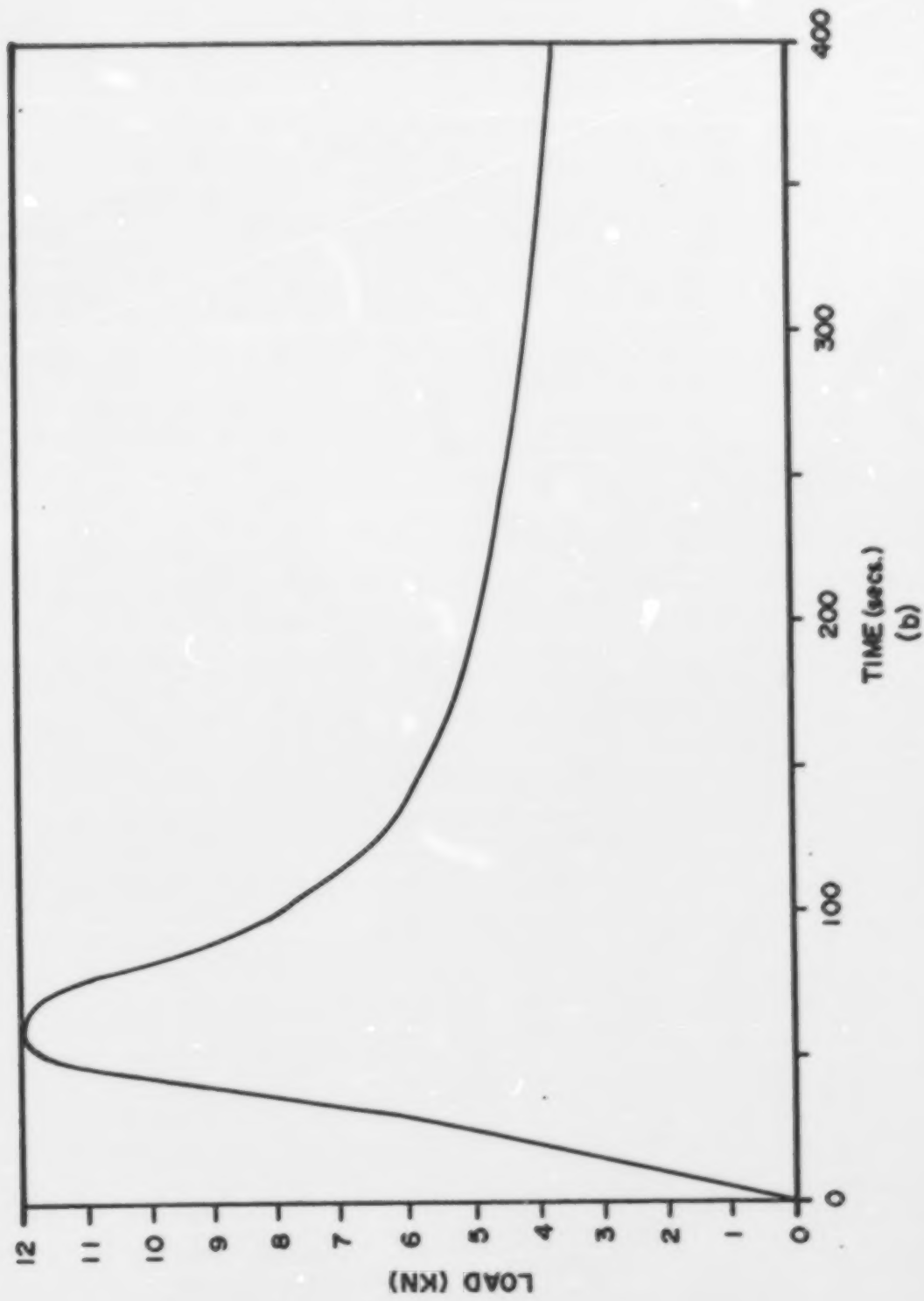


Fig. 2(b)

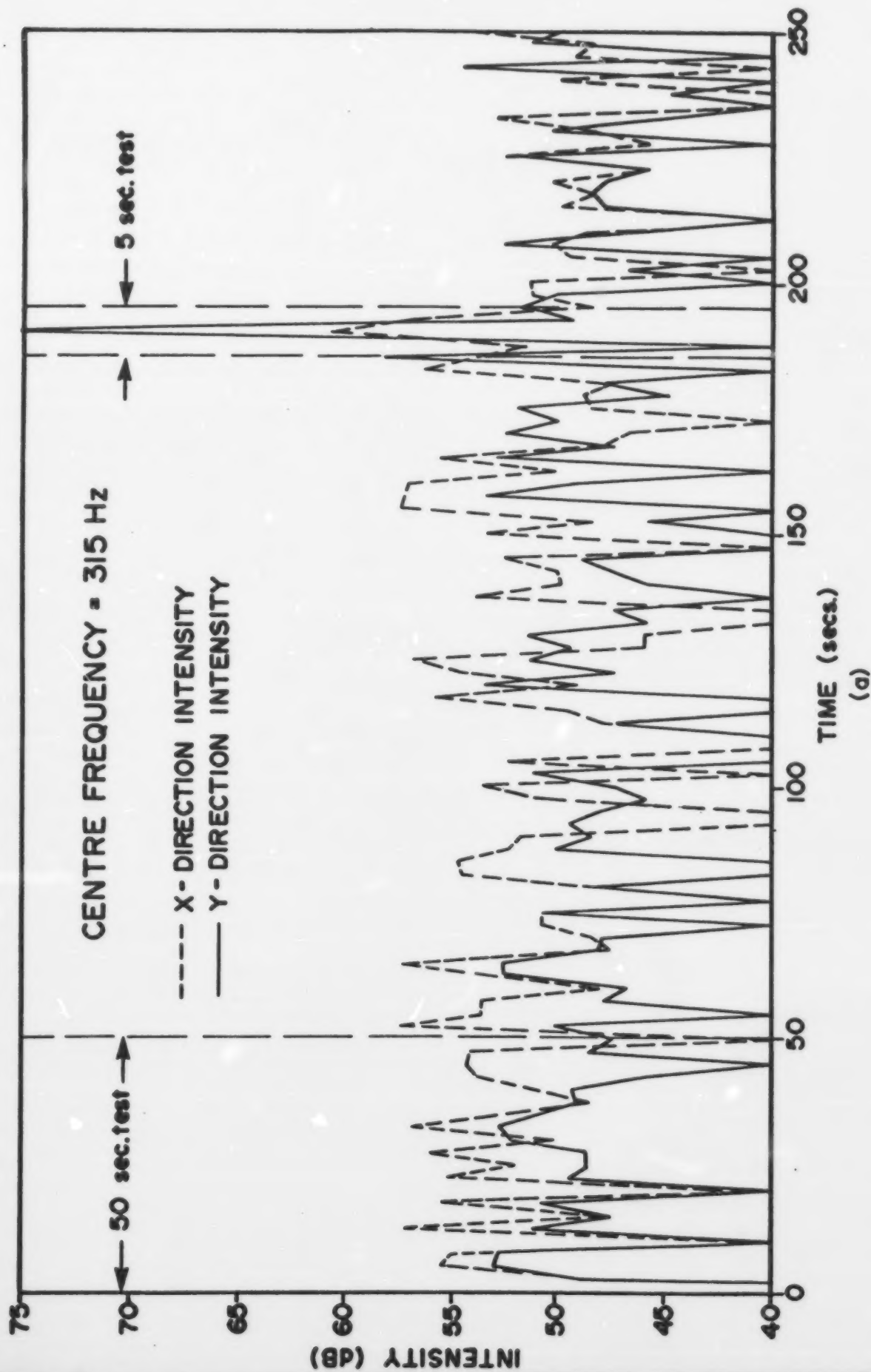


FIG 3(a)

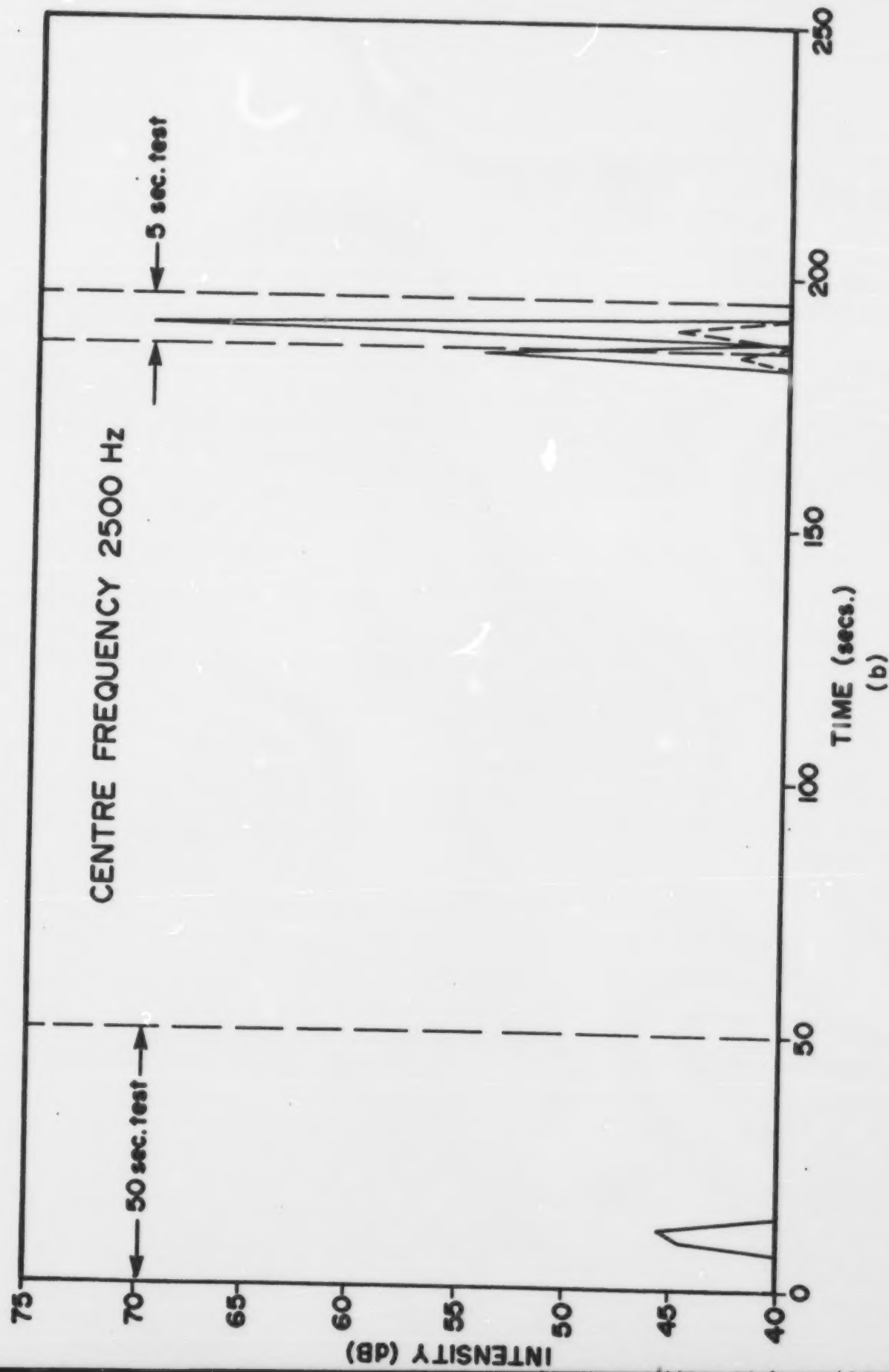


Fig. 3(b)

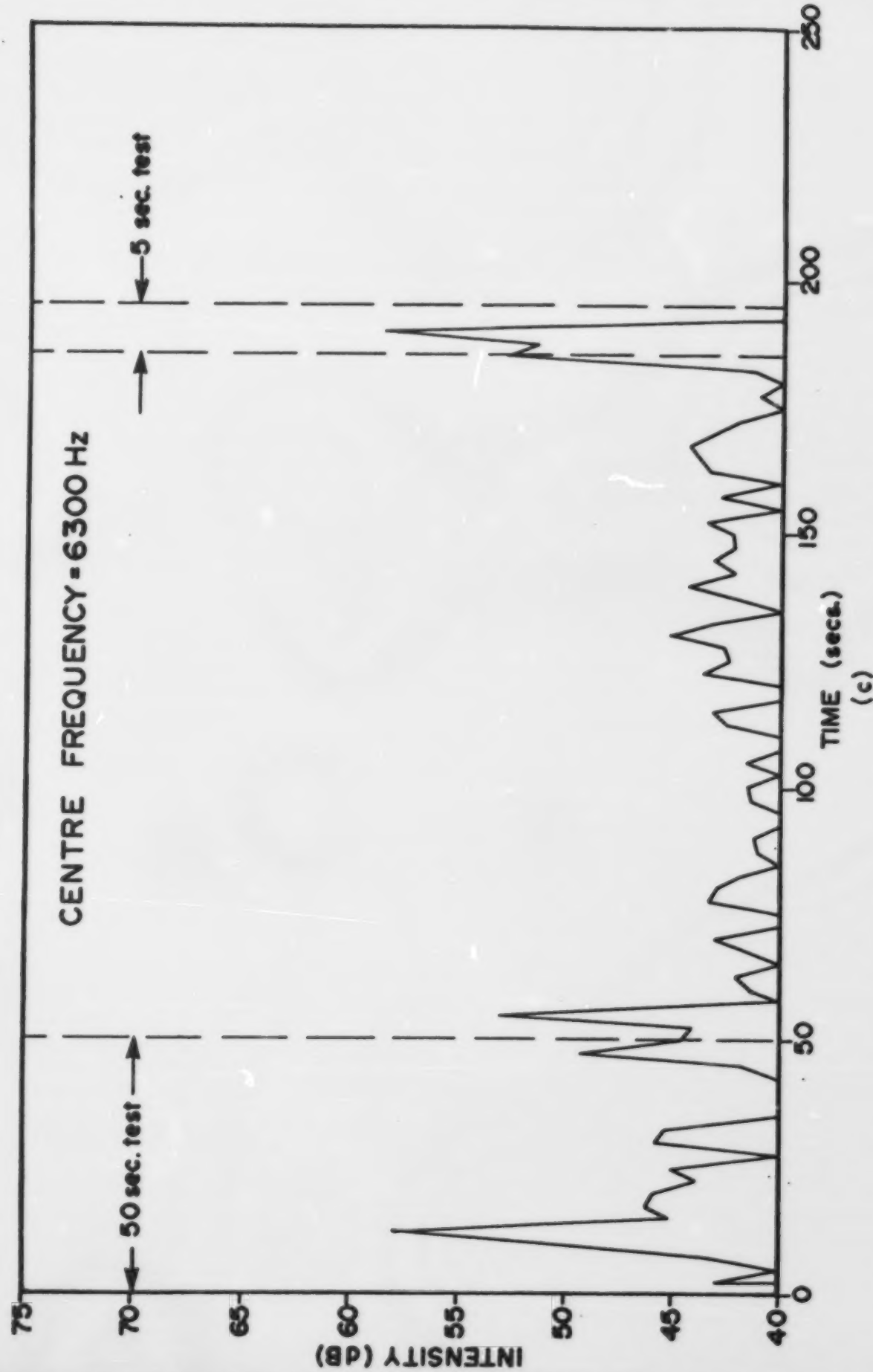


FIG. 3(c)

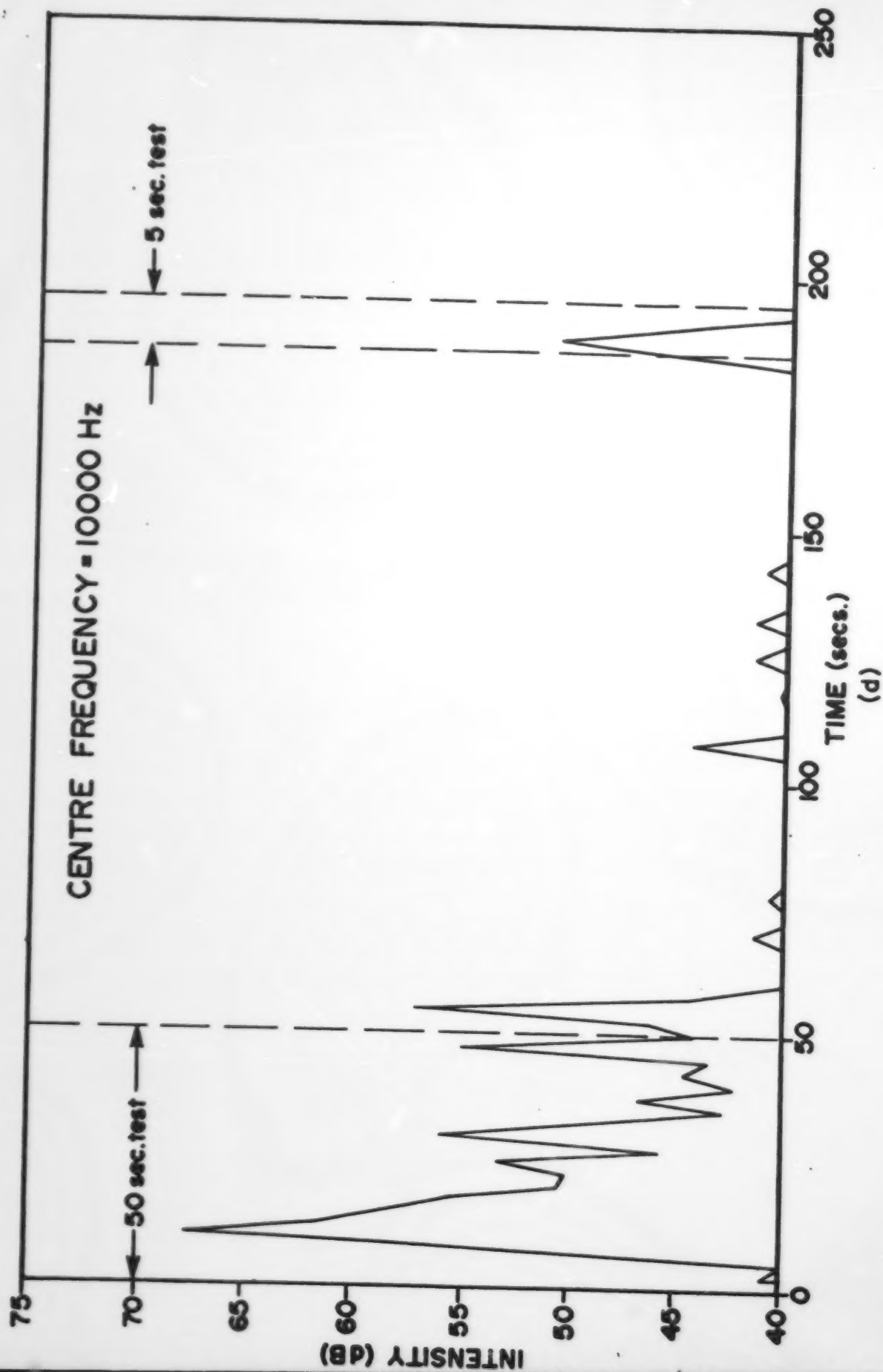
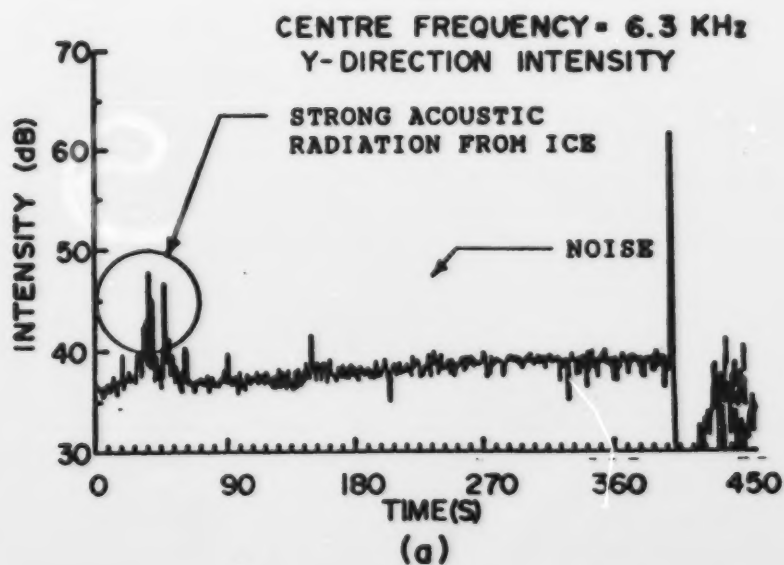
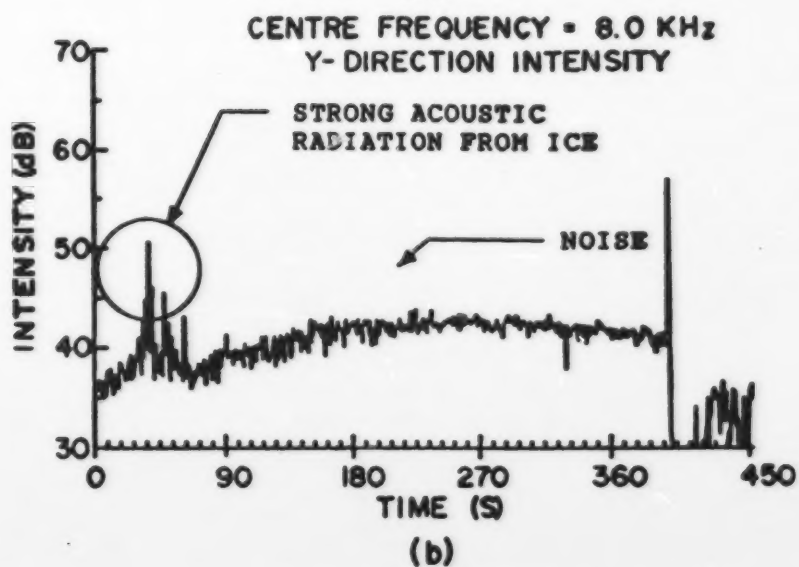
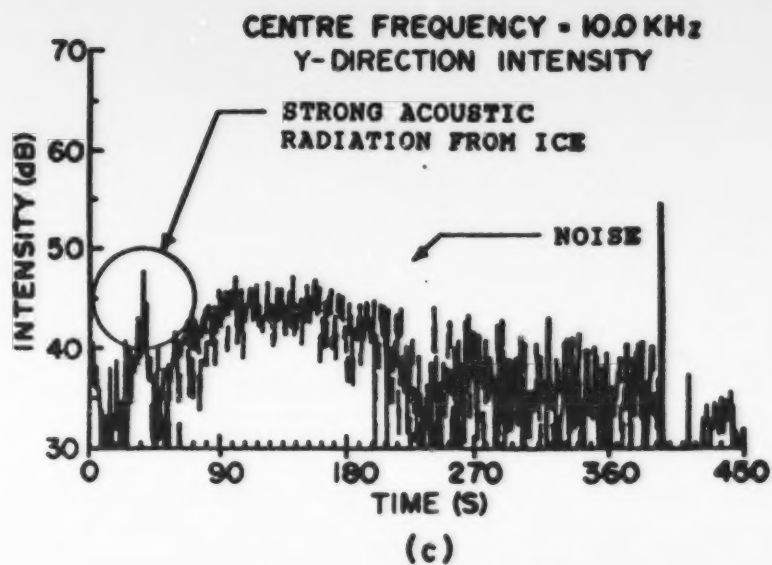


FIG. 3(d)

FIG. 4



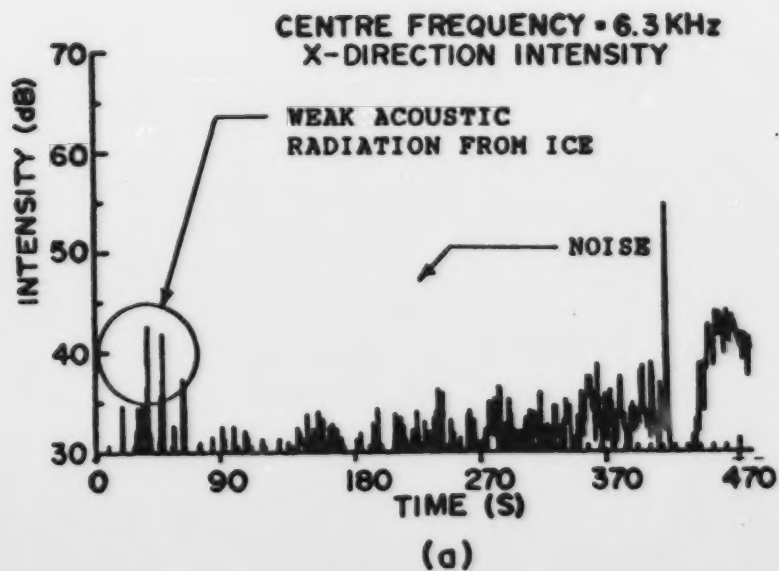
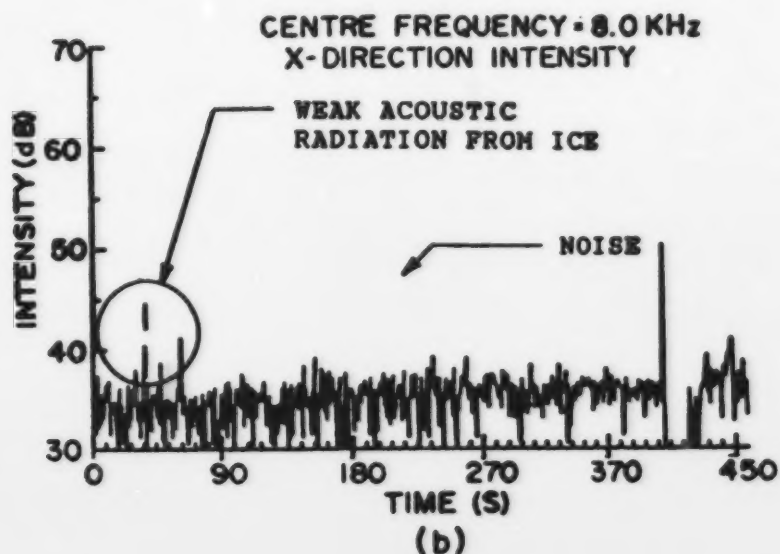
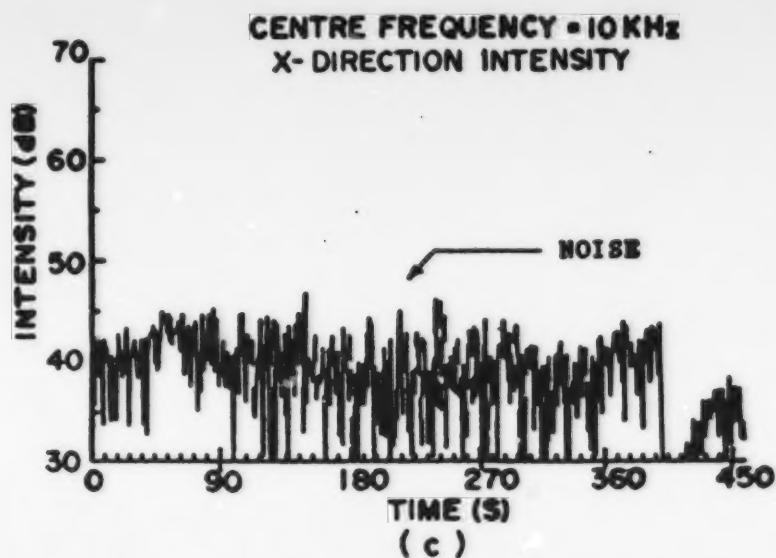
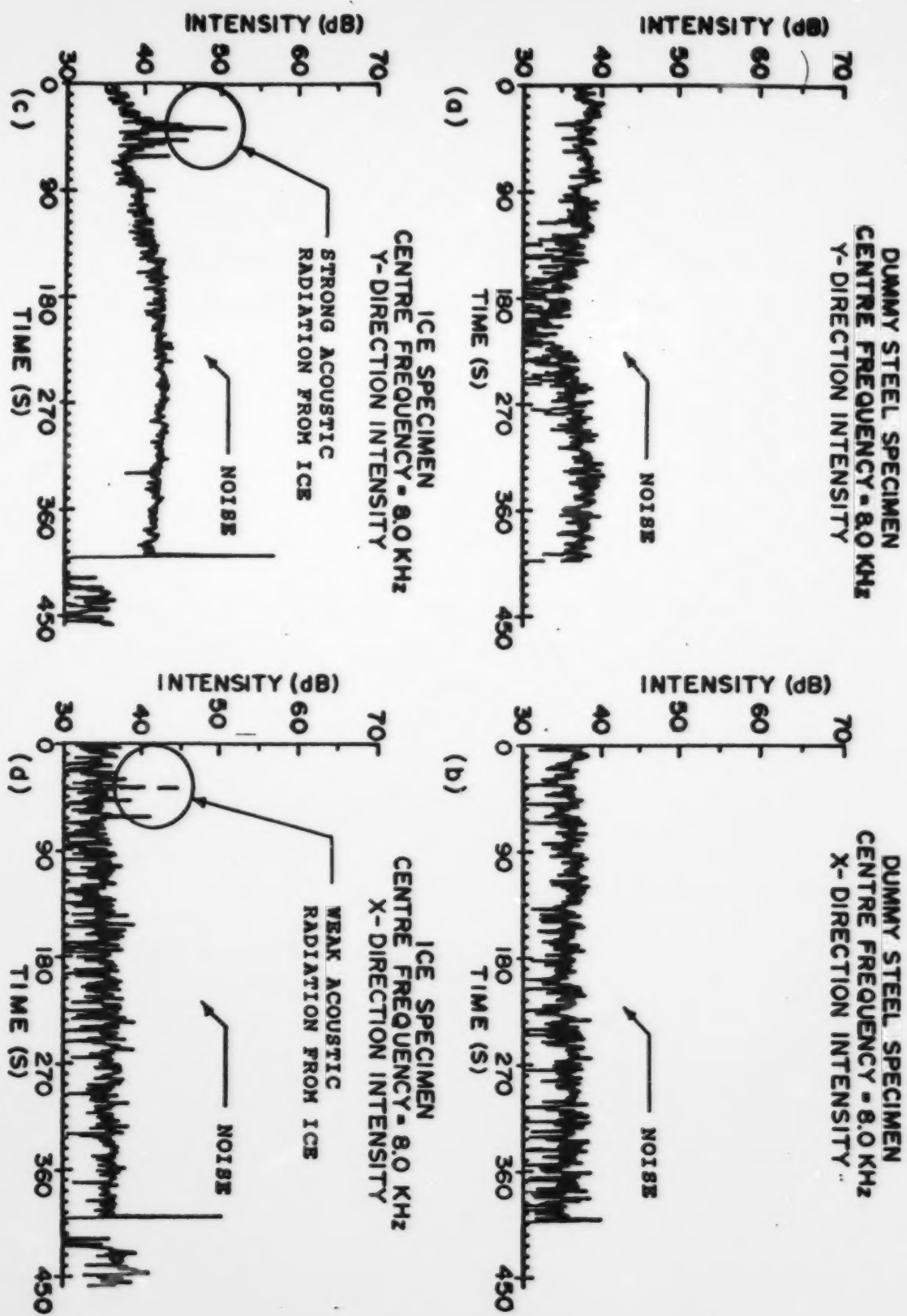


FIG. 6



200 100 Y C 8 217